



Integrate carbon dynamic models in analyzing carbon sequestration impact of forest biomass harvest

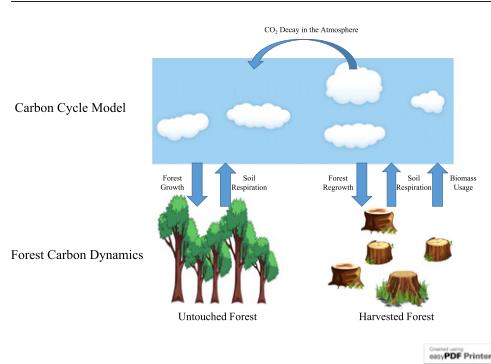
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HIGHLIGHTS

- Assess biomass harvest on carbon sequestration by integrating carbon dynamics models.
- Conduct assessment by a Chapman-Richards function and FVS with carbon cycle model.
- Reduce C sequestration impact by increasing growth and reducing harvest intensity.

GRAPHICAL ABSTRACT



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ABSTRACT

Biomass is an attractive natural energy resource for mitigating climate change. However, the loss of carbon sequestration as an ecosystem service due to biomass harvest has not been considered in previous studies. To assess the impact of biomass harvest on carbon sequestration, carbon dynamics in the forests and the atmosphere were integrated. The impact of forest biomass harvests on carbon sequestration was assessed based on the difference between carbon sequestration after harvest and carbon sequestration without harvest. A Chapman-Richards function and the forest vegetation simulator (FVS) were used to simulate the growth of a forest stand. The carbon dynamics in the atmosphere were simulated by the Bern2.5CC carbon cycle model. Characterization factors of the impact were calculated in three time horizons: 20-, 100- and 500-year. According to the simulations, postponement of harvest and low harvest intensity could prolong the compensation period. The annual impact on carbon sequestration was mostly negative over a short time and became positive in the end of compensation period. The highest characteristic factors of the impact on carbon sequestration were found in rotation length of 100 years with the time horizon of 500-year in the Chapman-Richards simulation and in the lowest harvest intensity with the time horizon of 500-year in the FVS simulation. Based on the results, increasing growth rate, postponing harvest, reducing harvest intensity and increasing length of time horizon could reduce the impact of forest harvest on carbon sequestration. The method proposed in this study is more proper to assess the impact on carbon sequestration, and it has much wider applications in forest management practice.

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1. Background

Under the requirement of mitigating climate change, biomass solicits mounting interest and is considered an attractive energy resource because of the promise of low carbon emissions (Ragauskas et al., 2006;

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Zeman and Keith, 2008). Biomass can be used to produce many bioproducts, such as ethanol, pellet fuel, electricity and diesel fuel (Paul, 2009; Snowden-Swan and Male, 2012; Hsu, 2012; Liu, 2015). As one of the largest underexploited resources of cellulosic biomass, forest biomass is identified as a potentially important feedstock for bioproducts (Perlack et al., 2005; Liu, 2015). Therefore, the utilization of forest biomass is encouraged by a number of investigators (Viana et al., 2010; UCS, 2012).

Biomass is generally presumed carbon neutral, given that emissions from biomass combustion are compensated by plant regrowth (Ragauskas et al., 2006; Zeman and Keith, 2008). Recently, researchers have become aware that the climate change impact of biomass utilization should not be ignored. Emissions from land use change (Johnson, 2009; Searchinger et al., 2009) and biomass supply chain (Ulgiati, 2001; Hill et al., 2006) are a significant portion of emissions in the life cycle of biomass utilization. Currently, researchers also noticed that CO₂ emission from biomass combustion, especially from forest biomass, could also have positive global warming potential (Cherubini et al., 2011; Liu et al., 2017). The values of GWP_{bio} (global warming potential of biogenic CO₂ emission) obtained in these studies were 0.13–0.62 and obviously not neutral (Cherubini et al., 2011; Guest et al., 2013; Liu et al., 2017).

Beyond the standpoints mentioned above, the biomass harvest could have more global warming impacts. If a forest was reserved, it will keep growing and have a positive carbon sequestration capacity. When harvest activity is postponed, significant benefits of carbon sequestration can be expected (Cherubini et al., 2011). Carbon sequestration is one of the important ecosystem services, which is defined as net annual rate of atmospheric carbon absorbed by an ecosystem. Therefore, the impact of forest biomass harvests on carbon sequestration (i.e., carbon loss) should not be ignored. However, this portion of carbon loss is excluded in traditional life cycle assessment (Zhang et al., 2010). Zhang et al. (2010) developed an “Ecologically-based LCA” to account this portion of carbon loss. Another approach was developed based on the difference between current land use and an optimal land use (Koellner et al., 2013). However, all these approaches ignored the complexity and dynamics of carbon sequestration in an ecosystem. Recently, researchers started to incorporate carbon dynamics models into the assessment of carbon loss (Levasseur et al., 2010; Arbault et al., 2014).

Although many advances have been achieved in the previous studies, no method has been proposed to estimate the impact of forest biomass harvest on carbon sequestration of a forest stand with consideration of carbon dynamics in both forest and the atmosphere (Haberl et al., 2012; Arbault et al., 2014). In this study, a new approach was proposed that integrated carbon dynamics models to account for this impact. We also studied the performance of this approach by simulations of two different forest growth models.

2. Methods

2.1. Forest stand modeling

In this study, two forest stand growth models were used to simulate the carbon dynamics of a forest stand. One was a combination of a Chapman-Richards function (Lenthall, 1986) and Yasso07 model (Tuomi et al., 2010). The other was Forest Vegetation Simulator (FVS; Dixon, 2013). The detailed description of the two simulations was in the following two subsections.

2.1.1. Chapman-Richards function and Yasso

The Chapman-Richards function is formulated as $B(a) = b_1(1 - e^{-b_2a})^{b_3}$, where a is stand age, $B(a)$ is biomass accumulation at stand age a and measured in tC/ha (tC: metric ton carbon equivalent), b_1 , b_2 and b_3 are empirical parameters based on earlier studies (Lenthall, 1986). This biomass accumulation function provides a reasonable growth estimation of a forest stand. As showed in Table 1,

three sets of parameter configurations were used to simulate growth of three different types of forest stands: i.e., a tropical rain forest (fast-growing), a temperate deciduous forest (moderate-growing) and a boreal forest (slow-growing).

The average available biomass is assumed to be a fraction (θ) of live biomass. Thus, the available biomass is calculated as $A(a) = \theta B(a)$, where $A(a)$ is the available biomass at stand age a and measured in tC/ha. In this study, θ was set to 0.5. Three rotation lengths were simulated for each type of forest stand, which were 30, 50 and 100 years, respectively. All the live biomass was reset to zero after the harvest activity, while biomass remaining in the field was considered dead organic matter (DOM). To assess the impact on carbon sequestration, a scenario of no harvest was also simulated for every forest stand.

The decomposition of DOM was simulated by Yasso07. This is a widely used model to simulate biomass decomposition in forest stands (Tuomi et al., 2010). The initial inputs of DOM into soil were 5% of leaf/needle and 45% of branch/stem/root. These initial inputs of DOM were averages of the inventory data by Zhang et al. (2015). Table 2 lists the average chemical composition of different biomass types (Liski et al., 2009). Based on the Yasso07 simulation, the decomposition rates of leaf/needle and branch/stem/root were represented as fractions of initial inputs (Fig. 1). The detailed parameter setting and calculation of Yasso07 simulation can be found in the supporting information.

2.1.2. FVS simulation

The FVS is a highly integrated system of forest growth simulation models (Dixon, 2013). This is a useful analytical tool that provided by U.S. Department of Agriculture. In this study, forest stands in three inventoried sites were randomly selected in the US. The inventory data are available at USDA Forest Service Website (https://apps.fs.usda.gov/fia/datamart/datamart_access.html). They were douglas fir stand in Washington (WA, 47°00'02.4"N 121°29'13.2"W), chestnut oak stand in West Virginia (WV, 39°17'28.3"N 78°36'09.0"W) and loblolly pine stand in Florida (FL, 30°23'32.8"N 83°27'23.8"W), respectively. Different variants of FVS were applied for different sites, East Cascades Variant (EC) for WA, Northeast Variant (NE) for WV and Southern Variant (SN) for FL. The simulations were conducted with Fire and Fuels Extension (FFE) program (Sharma, 2010; Saud et al., 2013). The clear-cut was scheduled under the conditions of at least 30 years after last harvest and 35%, 50% and 65% over normal stocking. Low percentage over normal stocking indicates high harvest intensity. Trees with a diameter larger than 5 cm were clear-cut by leaving 12 legacy trees (DBH > 30 cm) per hectare. The first harvest was assumed to occur in 2017. To assess the impact of carbon sequestration, a scenario of no harvest was also simulated for every forest stand.

2.2. Impact assessment

The impact of forest biomass harvest on carbon sequestration was assessed based on the difference between carbon sequestration after harvest and carbon sequestration without harvest. If a forest stand is not harvested, the annual carbon sequestration at stand age t is $\Delta B(t) = B(t) - B(t-1)$. Once the forest stand is harvested at stand age m , the biomass growth in the first few years should be accounted as compensation of biomass combustion. The compensation period is defined as the length of time required to fully compensate the biomass-derived carbon emissions remaining in the atmosphere. Determination of the compensation period can be found in the end of this section. Afterwards, the annual carbon sequestration by biomass growth is $\Delta B'(n) = B'(n) - B'(n-1)$, where $n = t - m$ and $B'(n)$ is biomass accumulation in the n^{th} year after harvest. Before the end of the compensation period, $\Delta B'(t)$ is set to zero.

At each harvest site, the annual carbon emissions from the DOM decomposition in the n^{th} year after harvest is calculated as $\Delta S(n) = S(n-1) - S(n)$, where $S(n)$ is the sum of carbon emissions

Table 1

Parameter settings for the Chapman-Richards function.

Set #	Growth rate	Forest type	b_1	b_2	b_3	Source
1	Fast	Tropical rain forest	428.01	0.0253	2.64	Liu et al., 2017
2	Moderate	Temperate deciduous forest	198.6	0.0253	2.64	Asante et al., 2011
3	Slow	Boreal forest	103.067	0.0245	2.69	Holtmark, 2015

from five compartments of DOM remaining in the soil. The five compartments are acid hydrolysables, water solubles, ethanol solubles, neither soluble nor hydrolysables and humus (Tuomi et al., 2010). Therefore, the annual difference of carbon sequestration (ΔB_{net}), due to harvest, is as follows:

$$\Delta B_{net}(n) = [\Delta B'(n) - \Delta S(n)] - \Delta B(t) \quad (1)$$

Due to the decay of carbon emissions in the atmosphere in the interaction of ocean-atmosphere systems, a discount effect needs to be considered when summarizing the total impact (T) on carbon sequestration. In this study, we assume all the carbon emissions are CO_2 , and the remaining fraction is $y(n)$ in the n^{th} year after harvest. Thus,

$$T = \int_0^{TH} \frac{\Delta B_{net}(n)}{y(n)} \quad (2)$$

$$y(n) = y_0 + \sum_{i=1}^3 y_i e^{-n/\tau_i} \quad (3)$$

where TH is the time horizon; $y(n)$ is the fraction of the initial emission of CO_2 at time n , while y_i and τ_i are estimated parameters. The choices of time horizons are 20-, 100- and 500-year, i.e., the same time horizons in estimating the GWP of greenhouse gases by the IPCC (Stocker, 2014). The CO_2 decay model (Eq. 3) is based on the Bern2.5CC carbon cycle model using a CO_2 concentration of 378 ppm in the atmosphere (Joos et al., 2013). The parameters are fitted from a set of climate models and set as $y_0 = 0.217$, $y_1 = 0.224$, $y_2 = 0.282$, $y_3 = 0.276$, $\tau_1 = 394.4$, $\tau_2 = 36.54$, $\tau_3 = 4.304$ (Joos et al., 2013). The decay curve of CO_2 within 500 years is shown in Fig. 2.

To integrate the total impact T to life cycle inventory (LCI) data which is a critical basis for life cycle assessment, the total impact is divided by a magnitude of a perturbation. The result is a characterization factor (CF) which indicates the impact on carbon sequestration due to the perturbation (p):

$$CF = \frac{T}{p} \quad (4)$$

In this study, characterization factors due to acreage of forest stand harvested (CF_a : tC/ha) and tonnage of biomass harvested (CF_b : tC/tC) were considered.

The compensation period is determined by the decay of carbon emissions and growth of biomass. When the forest is harvested for biomass, the initial pulse of CO_2 is E . Let $E_h(n)$ as CO_2 emission remaining in the atmosphere at time n . The compensation period ends when $E_h(n) \leq 0$

(Liu et al., 2017). Hence, the following equations were derived, and detailed explanation can be found in the supporting information:

$$E_h(0) = E \quad (5)$$

$$E_h(n+1) = \frac{y(n+1)[E_h(n) - \Delta B'(n)]}{y(n)} \quad (6)$$

3. Results

3.1. Length of compensation period

Biomass-derived carbon emissions have a smaller impact on climate change than fossil fuel-derived carbon emissions (Liu, 2015). The main reason is biomass-derived carbon emissions can be offset by biomass regrowth. Therefore, if the biomass-derived carbon emissions remain in the atmosphere, the growth of a forest stand should be primarily used to compensate biogenic CO_2 emission. The length of this period to compensate biogenic CO_2 emission, defined as the compensation period, was determined to analyze the impact of harvest.

According to the computational results, the length of compensation periods in the Chapman-Richards simulation had no significant difference among different forest types (Fig. S1 in the supporting information). The length was 18, 25 and 35 years when the rotation was 30, 50 and 100 years, respectively. The compensation of fast-growing forest stand with rotation length of 50 years was shown in Fig. 3a to illustrate the dynamics of biogenic CO_2 emission compensation. All the other cases could be found in Fig. S1 in the supporting information.

In the FVS simulation, the clear-cut was conducted based on a percentage above normal stocking. Thus, no consistent compensation period was found in each harvest intensity (Fig. 3b, Fig. S2). However, in the study of biomass-based compensation period which was defined as the length of compensation period divided by tonnage of biomass harvested within the time horizon, a significant reduction of biomass-based compensation period was found with the reducing of harvest intensity (i.e., increasing percentage of normal stocking, Table 3).

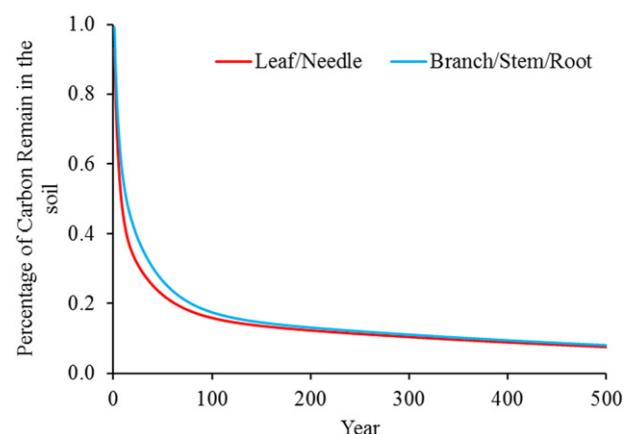


Fig. 1. Decomposition of biomass simulated by Yasso07: (a) branch/stem/root; (b) leaf/needle.

Table 2

Chemical compositions of different biomass types.

Type	Acid hydrolysables	Water solubles	Ethanol solubles	Neither soluble nor hydrolysables
Leaf/needle	45%	24%	9%	22%
Branch/stem/root	52%	2%	6%	40%

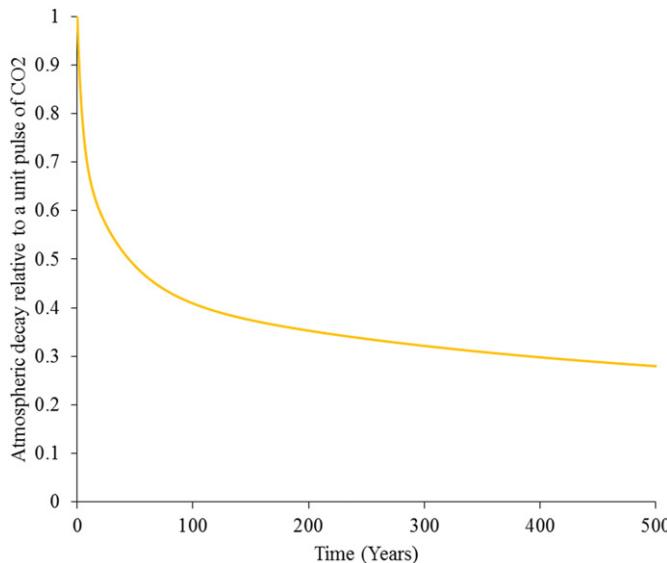


Fig. 2. Decay curve of CO₂ emission in the atmosphere.

3.2. Carbon dynamics and impact on carbon sequestrations

To analyze the loss of carbon sequestration due to harvest, the annual impact of harvest on carbon sequestration was calculated as $\frac{\Delta B_{net}(n)}{y(n)}$. A negative impact implies a positive global warming impact of a harvest activity. Within the compensation period, the annual impact was always expected to be negative.

In the Chapman-Richards simulation, the negative annual impacts were ended right after the end of the first compensation period in all cases (Fig. S3). However, the period of negative annual impact could be longer than the compensation period if the growth rates after harvest were still lower than the growth rate of the untouched forest after the end of the compensation period. Fig. 4a shows the carbon balance of a fast-growing forest stand harvested every 50 years and not harvested. The carbon sequestration rates of a harvested and unharvested forest stand and carbon emissions from DOM could be found within the time horizons. The trends of all curves in the Chapman-Richards simulation were similar in different forest types (Fig. S3).

In the FVS simulations, the annual impact within the compensation period was also negative (Fig. 4b). The untouched forest changed to a carbon source in a very short time (Fig. S4). However, the emission from DOM after harvest was still considerably high in the end of

Table 3
Biomass-based compensation period in the FVS simulation: year/tC.

Forest location	Harvest intensity (% above normal stocking)		
	35	50	65
FL	0.613	0.513	0.423
WA	0.354	0.354	0.354
WV	0.401	0.361	0.317

compensation period, and positive annual impact could not be expected before the growth rate after harvest exceeded emissions from DOM.

3.3. Characterization factors in different scenarios

As Table 4 shows, the CF_a in the Chapman-Richards simulation is less negative when the rotation length become longer in $TH = 100$ and 500 . When $TH = 500$, the CF_a in all scenarios were positive. The CF_b had the similar trend as the CF_a . From fast-growing to slow-growing forest stands, the difference reduced between the highest and the lowest impact in the same stand. The differences were 1555.365 in fast-growing stand and 402.727 in slow-growing stand. However, the differences of the CF_b between the highest and the lowest value in the same stand increased from fast-growing to slow-growing forest stands.

Table 5 shows the results of characterization factors in the FVS simulation. Lower harvest intensity usually had a less negative impact, especially when $TH = 100$ and 500 . When $TH = 500$, all the CF_a became positive except the value in FL under the highest harvest intensity and the values in WA. The CF_b had the similar trend as the CF_a in the FVS simulation.

4. Discussion

4.1. Compensation period

Due to biomass regrowth by photosynthesis to compensate biogenic CO₂ emission, the use of biomass for bioenergy has significant advantages over fossil fuels in terms of GHG emissions (Liu, 2015). Therefore, when estimating the impact of biomass harvests on carbon sequestration, the length of this compensation period is critical. In our study, the length of the compensation period was determined when the initial pulse of biogenic CO₂ emission was fully offset by biomass regrowth. Based on the results of the Chapman-Richards simulation, we found that a long rotation length required a long compensation period. However, long compensation period indicates high GWP of biogenic CO₂ emissions (Cherubini et al., 2011; Liu et al., 2017). Therefore, postponing biomass harvesting can increase GWP of biomass-derived CO₂ emission.

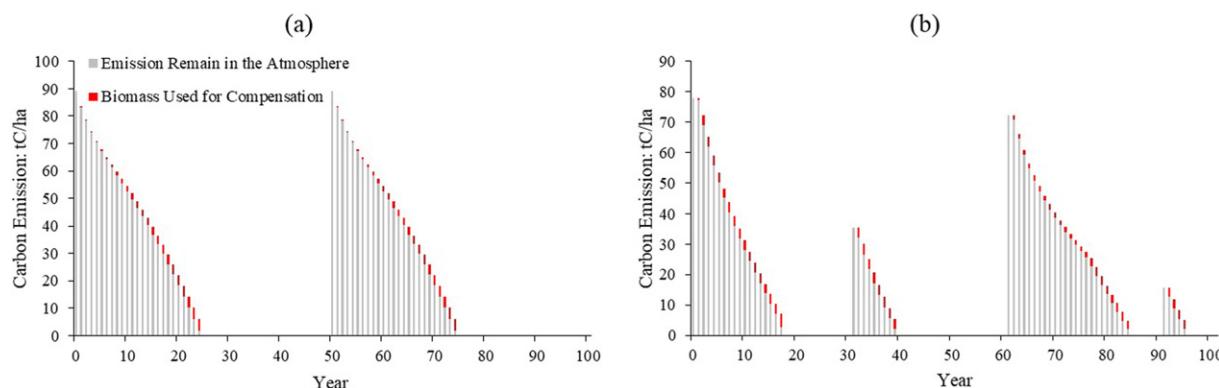


Fig. 3. Compensation periods of a) fast-growing forest stand with rotation length of 50 years and b) forest stand in WV with harvest intensity of 35% above normal stocking. Emission Remain in the Atmosphere: the amount of CO₂ emission that remains in the atmosphere after the one-time pulse. Biomass Used for Compensation: the amount of biomass from forest regrowth annually that was used to offset the CO₂ emission in the atmosphere.

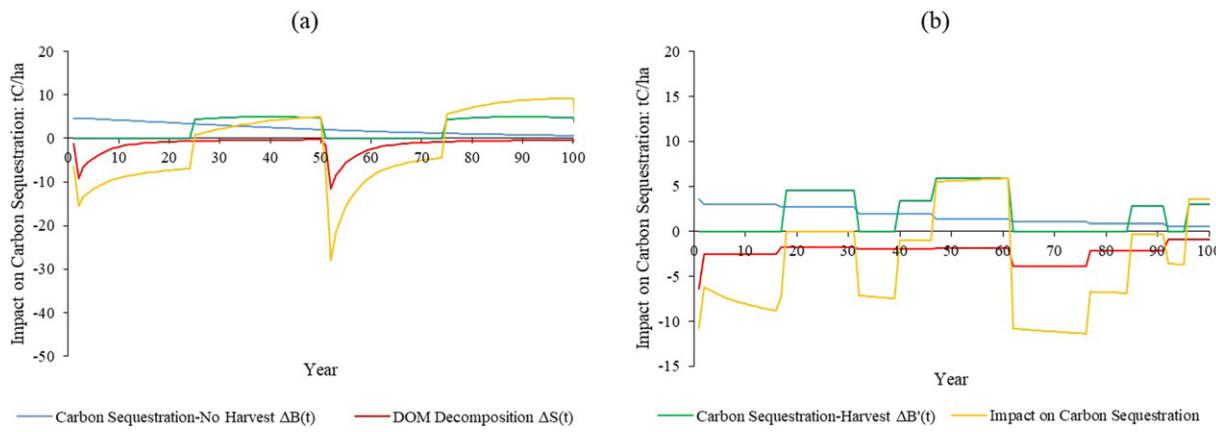


Fig. 4. Carbon sequestration and emissions by a) fast-growing forest stand with rotation length of 50 years and b) forest stand in WV with harvest intensity of 35% above normal stocking. Carbon Sequestration-No Harvest $\Delta B(t)$: the annual carbon sequestration rate of an untouched forest stand. DOM Decomposition: carbon emissions from the decomposition of dead organic matter after harvest. Carbon Sequestration-Harvest $\Delta B'(t)$: the annual carbon sequestration rate of the forest stand after harvest. Impact on carbon sequestration: the different between $\Delta B(t)$ and $\Delta B'(t)$ with the consideration of decay of CO₂ emission in the atmosphere.

There are two main reasons for this result. The first is the higher biomass accumulation when the harvest was postponed. The second is that, for the same forest type, the growth rate of a forest stand was the same at the same stand age. In the FVS simulation, lower harvest intensity had shorter biomass-based compensation period. This indicates that biomass in the lowest harvest intensity is expected to have the lowest GWP of biogenic CO₂ emissions. The reason for this result is that low intensity of biomass harvest ensures fast re-growth of biomass (Sharma, 2010; Saud et al., 2013).

4.2. Impact on carbon sequestration

Based on the simulations of the two forest stand growth models (Chapman-Richards function and FVS), the impact of harvests on carbon sequestration is negative within compensation period. This is a reasonable result since biomass regrowth is primarily used to offset biogenic CO₂ emission. In this period, no regrowth is allocated to offset the emissions from DOM and the loss of carbon sequestration. After the end of the compensation period, the annual impact on carbon sequestration quickly became positive. The main reason is attributed to the slow growth of old age forest stands in our simulations. If a forest stand has higher growth rate at old age than in this study, the impact due to harvest would require more time to have a positive annual impact on carbon sequestration. In the Chapman-Richards simulation, we generalized the Yasso model without considering the effect of regional climate (Tuomi et al., 2010). If the effect of climate was simulated, a higher decomposition rate in the tropics would also postpone the time where the annual impact became positive (Repo et al., 2011). When calculating the impact on carbon sequestration, a discount effect which considered the dynamics of carbon in the atmosphere was included in our study. This discount effect expanded the annual impact along

time. Levasseur et al. (2010) and Arbault et al. (2014) also developed approaches to summarize the impact. However, their estimations were too conservative because they ignored the interaction of ocean-atmosphere system which can significantly accelerate the decay of CO₂ emission.

4.3. Characterization factors

Different time horizons were selected to assess the impact of forest harvest on carbon sequestration. Negative impact values indicated that biomass harvest caused a loss of carbon sequestration. A time horizon of 20-year was near the end of the compensation period (18 years) or within the compensation period (25 and 35 years) in the Chapman-Richards simulation. Thus, most of the annual impacts were negative, and a negative CF_a was obtained when $TH = 20$. At this time horizon, the negative impact was the highest when the stand was harvested at age 50. This is due to the highest growth rates of a forest stand at age 50 to 70. When the time horizon was long ($TH = 500$), benefits of forest harvest could be expected because of a positive annual impact after the end of compensation period. Postponing a harvest could benefit carbon sequestration when the time horizons were 100- or 500-year. Similar results were found in previous analyses (Cherubini et al., 2011; Zeng et al., 2013). This is mainly attributed to the slow growth in an old forest stand. The differences in impact on carbon sequestration among various tree species are the result of the different biomass accumulations and growth rates among tree species. Postponement of harvest could alleviate the loss of carbon sequestration. However, postponement of harvest would increase the GWP of biogenic CO₂ emission. The balance between the loss of carbon sequestration and GWP of biogenic CO₂ emission requires further discussion in future studies. In the FVS simulation, low harvest intensity had low loss of carbon sequestration in the time

Table 4
Characterization factors of different scenarios in the Chapman-Richards simulation.

Growth rate	TH	CF_a (tC/ha)			CF_b (tC/tC biomass)		
		RL-30	RL-50	RL-100	RL-30	RL-50	RL-100
Fast	20-Year	-149.811	-189.162	-179.988	-0.218	-0.212	-0.209
	100-Year	-403.237	-146.829	172.686	-0.587	-0.165	0.201
	500-Year	745.557	732.389	1152.128	1.085	0.821	1.341
Moderate	20-Year	-69.513	-87.773	-83.516	-0.218	-0.212	-0.209
	100-Year	-218.421	-68.130	80.128	-0.685	-0.165	0.201
	500-Year	52.377	339.834	534.597	0.164	0.821	1.341
Slow	20-Year	-34.736	-39.425	-43.283	-0.230	-0.195	-0.214
	100-Year	-115.953	-40.906	40.033	-0.768	-0.202	0.198
	500-Year	14.185	165.005	286.774	0.094	0.817	1.419

Table 5

Characterization factors of different scenarios in the FVS simulation.

Growth rate	TH	CF _a (tC/ha)			CF _b (tC/tC biomass)		
		HI-35	HI-50	HI-65	HI-35	HI-50	HI-65
FL	20-Year	−50.661	−44.603	−44.603	−0.124	−0.087	−0.141
	100-Year	−328.418	−232.677	−307.425	−0.801	−0.454	−0.970
	500-Year	−5.066	143.186	597.735	−0.012	0.279	1.887
WA	20-Year	−199.550	−199.550	−199.550	−1.312	−1.137	−0.739
	100-Year	−771.694	−723.618	−367.848	−5.074	−4.123	−1.363
	500-Year	−514.370	−474.494	−272.987	−3.382	−2.704	−1.011
WV	20-Year	−134.311	−136.463	−138.107	−0.226	−0.250	−0.481
	100-Year	−334.434	−316.183	−293.824	−0.564	−0.579	−1.023
	500-Year	156.444	522.078	787.285	0.264	0.956	2.742

horizon of 100- and 500-year. This is because untouched forest stands simulated by FVS became carbon sources after a period of growth. In WA, the stand stopped growth after the second cut. Thus, the impact of harvest under all intensity were negative in all time horizons. In both forest growth model simulations, less negative CF_b were found in longer rotation length and lower harvest intensity. This indicates that obvious benefit of long rotation length and low intensity could be expected in terms of carbon sequestration.

4.4. Robustness and future study

In this study, a new method was proposed to account carbon loss (i.e., impact on carbon sequestration) due to forest biomass harvest. The main purpose of this study was to develop a more reasonable measurement for the impact of forest biomass harvest on carbon sequestration. In this study, two forest growth models were used to describe the application of this method. Although the results were obvious, a quantitative assessment of the impact on carbon sequestration is essentially necessary. Besides the application in this study, this method could generally have a much wider application in forest management practice. The carbon loss by different harvest methods and different harvest strategies could also be estimated with this method. Natural disturbances, such as wildfire, insect burst and climate change, could cause net carbon emissions in a forest (Denman et al., 2007; Jenkins et al., 2008). The impact of natural disturbances could be estimated properly by this method. Moreover, this method is suitable to estimate the carbon loss by land use change (Searchinger et al., 2008).

To improve the estimation accuracy of carbon loss, more deep studies are required in the future. The model of carbon dynamics is critical. However, the estimation of carbon dynamics is very complex due to many factors are involved, such as ecosystem type, tree stand age, soil type and elevation (Adamus et al., 2000). The simulations in this study were examples to describe the method of carbon loss estimation. The other different carbon dynamics models could obtain different simulations of carbon dynamics, such as CENTURY (Parton et al., 2001), CBM-CFS3 (Carbon Budget Model of the Canadian Forest Sector, Kurz et al., 2009), CO2FIX (Schelhaas et al., 2004). Therefore, intensive validation of carbon dynamics models and endeavor of governments could assist researchers to develop guidelines to select the most suitable carbon dynamics model. For the natural disturbances, it is affirmed that they could have significant effects on carbon dynamics (Denman et al., 2007; Jenkins et al., 2008). However, the behaviors of the natural disturbances are difficult to simulate (Denman et al., 2007). Some innovative studies had been conducted, such as Weibull distribution of wildfire frequency (Moritz et al., 2009) and Poisson distribution of burn area (Malamud et al., 2005). However, generally accepted models are still in need.

5. Conclusions

Based on the approach proposed in this study, several inferences can be drawn according to the simulations. In the Chapman-Richards

simulation, postponement of harvest can prolong the compensation period which increases the GWP of biogenic CO₂ emission. In the FVS simulation, the biomass-based compensation period is longer in higher harvest intensity. This compensation period ends when biogenic CO₂ emission is fully absorbed. Therefore, the annual impact of a harvest on carbon sequestration is negative over a short time and becomes positive over a long time. The characterization factors due to different perturbations generally become less negative with longer rotation length in the Chapman-Richards simulation and lower harvest intensity in the FVS simulation. This method can be applied to much wider situations besides forest biomass harvest. However, before broadening the application, more studies are required in the future to improve carbon dynamics models and natural disturbance simulations.

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Authors' contribution

In this study, Yan Yan is responsible for the scientific work.

Competing interest

The author declare that she have no competing interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2017.09.326>.

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